International Journal of Earthquake Engineering and Geological Science (IJEEGS)
Vol. 7, Issue 1, Feb 2017, 1-14

SEISMIC PROPERTIES AND AUTOREGRESSIVE CONDITIONAL HETEROSKEDASTIC CHARACTERS OF EARTHQUAKES IN TAIWAN

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ABSTRACT

Four purposes are set for this paper. The first one is to find out the statistic properties of 3,085 labeled earthquakes data recorded in the seismic archive of the Central Weather Bureau (CWB) of Taiwan from January 1995 to October 2016.Hualien, a county in the east of Taiwan, has the most frequent number of earthquakes with1, 256 out of 3,085 times (40.7%) occurring there. Yilan County ranked second with a total of 524 earthquakes, which accounts for 17.0%. Most of earthquakes in Taiwan's twenty municipal cities and counties are categorized to be shallow (<70km), except Keelung, which has average hypocenters of 104.61 km (intermediate-depth). Maybe it is because earthquakes in Keelung are in the submerged tectonic plate. In the past 262 months (January 1995 to October 2016) the strongest magnitude (Richter scale, M_L) is 7.3, which occurred on September 21, 1999 in Nantou County and took away 2,415 lives as well as injured 11,305 people (wiki/921_earthquake).

The second purpose of this paper is to find out whether the time series of monthly number of earthquakes in the past 262 months in Hualien and Yilan are stationary or not. The author uses Augmented Dickey-Fuller (ADF) unit-root testing method to check the stationarity of the time series, and the results show that both Hualien and Yilan reveal to be stationary.

The third purpose is to check whether the time series of the monthly number of earthquakes in both counties are co-integrated or not. The outcome shows the time series of Hualien and Yilan are co-integrated, and no spurious effect exists. The regression equation shows that a unit increase of earthquake in Hualien may result in an increase of 0.2149 unit earthquake in Yilan.

The fourth purpose is to find out whether the autoregressive conditional heteroskedastic (ARCH) variances of the monthly number of earthquakes in both counties exist or not. The ARCH test shows the volatile variances of time series for both Hualien and Yilan are heteroskedastic.

KEYWORDS: CWB Archive, ARCH Model, Heteroskedastic

Received: Dec 03, 2016; **Accepted:** Jan 03, 2017; **Published:** Jan 09, 2017; **Paper Id.:** IJEEGSFEB20171

Original Article

INTRODUCTION

Earthquake forecasting has long been an area that scientists are eager to explore, but up to now there seem no reliable methods available. Can earthquakes be forecasted accurately? If can, where, when, and what magnitude will it be? These questions have bothered scientists for a long time, and are worthy of study.

The author tries to use earthquake records in Taiwan, together with time series models to find out seismic properties of them in each city and county. Twenty (20) municipal cities and counties of Taiwan, Republic of China (R.O.C.), are used in this study. They are, Yilan, Hualien, Taitung, Nantou, Keelung, Taipei, New Taipei,

Taoyuan, Hsinchu, Miaoli, Taichung, Changhua, Yunlin, Chiayi, Tainan, Kaohsiung, Pingtung, and three islets Penghu, Kinmen, and Matsu. Such an arrangement is based on the geographical locations from east, central, and to the west of Taiwan.

Earthquake data are obtained from the Central Weather Bureau (CWB) public archive (CWB, 2016), and each earthquake belonging to which area is based on the name given by the CWB. There are labeled (given earthquake number) and unlabeled records of earthquakes (small scale) on the report of CWB. In this study, only labeled earthquakes (with numbers) are used, and unlabeled ones (with records, but no number) are discarded because their influence may be just localized or insignificant. The earthquake label always starts from number one at the beginning of each year, and the name of each earthquake is based on the closest seismometer location to the epicenter.

PROPERTIES OF EARTHQUAKES OF EACH CITY/COUNTY OF TAIWAN

Totally 3,085 earthquakes are recorded by the Central Weather Bureau from January 1995 to October 2016 (262 months). After tedious data manipulation and arrangement, the number of earthquakes in each city and county are summarized in the following table:

Table 1: Earthquake Data for Each City and County in Taiwan (From January 1995 to October 2016)

City/County	Numbers of Earthquakes	Mean Times Per Month	Mean Times Per Year	Earthquake Percentage (%)	Depth (km)	Magnitude (Richter M_L)		Total Energy Released (Ergs)	Averaged Time (Days)
						Mean	Max		
Yilan	524	2.04	24.48	17.0	36.56	4.42	7.1	6.40E+22	15.00
Hualien	1,256	4.88	58.57	40.7	16.7	4.22	6.9	1.12E+23	6.34
Taitung	412	1.59	19.10	13.4	18.66	4.57	7.1	6.45E+22	19.2
Nantou	192	0.76	9.10	6.2	15.97	4.55	7.3	1.08E+23	39.64
Keelung	20	0.07	0.86	0.6	104.61	5.52	7.2	9.11E+22	341.33
Taipei	12	0.05	0.57	0.4	26.91	3.55	5.1	3.48E+19	581.48
New Taipei	2	0.01	0.10	0.1	9.7	3	3.3	6.33E+16	232.8
Taoyuan	9	0.04	0.43	0.3	11.77	3.92	4.7	1.54E+19	614.97
Hsinchu	14	0.05	0.62	0.5	7.95	3.84	5	3.61E+19	437.67
Miaoli	35	0.14	1.67	1.1	8.92	4.35	5.2	1.96E+20	171.11
Taichung	60	0.24	2.86	1.9	16.02	4.28	5.6	6.14E+20	115.15
Changhua	8	0.03	0.38	0.3	13.34	4.29	5.3	7.44E+19	769.84
Yunlin	103	0.41	4.90	3.3	11.23	4.14	6.6	5.43E+21	63.60
Chiayi	238	0.94	11.33	7.7	10.21	4.08	6.4	6.19E+21	31.95
Tainan	80	0.31	3.76	2.6	15.9	3.95	5.4	2.34E+20	99.00
Kaohsiung	28	0.11	1.33	0.9	35.46	4.17	5.8	6.97E+20	252.96
Pingtung	90	0.35	4.14	2.9	26.43	4.74	7	563E+22	85.69
Penghu	2	0.01	0.10	0.1	33.25	4.45	4.7	8.34E+18	39.04
Kinmen	0	0.00	0.00	0.00	N.A.	N.A.		N.A.	N.A.
Matsu	0	0.00	0.00	0.00	N.A.	N.A.		N.A.	N.A.
Total	3,085	N.A.	N.A.	100	N.A.	N.A.		5.09E+23	N.A.
Energy (ergs)	$\log_{10}E=11.8+1.5M_S$								
Averaged Time (days)	The average days between two earthquakes.								

In the above table, the energy of earthquakes released is based on the equation, $\log_{10}E=11.8+1.5M_S$, given by Gutenberg and Richter (Kramer, 1996). Many variations of M_S (shear-wave magnitude) formulas take into account the effects of specific geographic regions, so that the final computed magnitude is reasonably consistent with Richter's original

definition of M_L (Pidwirny, 2011). In this study, the author does not distinguish these two magnitudes. During the energy calculation, M_S was substituted by M_L.

Number of Earthquakes in Each City and County

This subsection is used to find the earthquake frequencies of each city and county in Taiwan for the past 21 years and 10 months (262 months) from January 1995 to October 2016. Both bar and PI charts are used to identify number and percentage (%) of earthquakes in each locality. The yearly number of earthquakes in Taiwan is shown in the following graph.

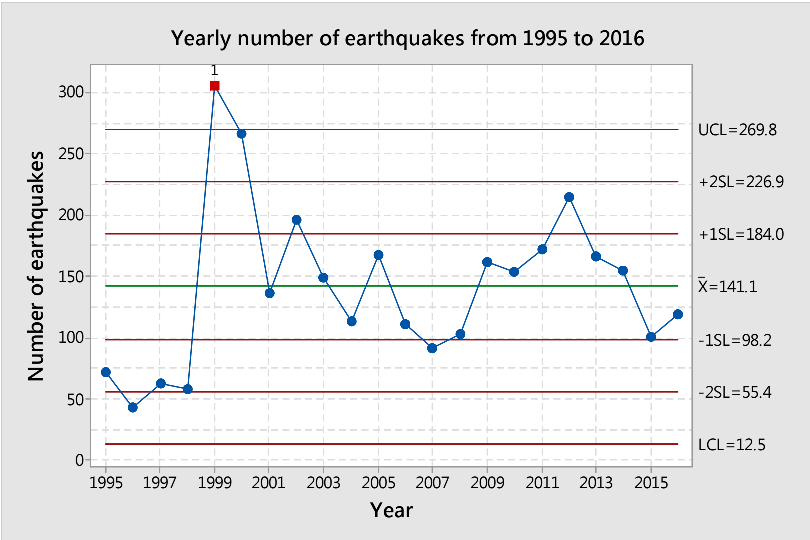

Figure 1: Number of Earthquakes per Year from Years 1995 to 2016 (Expected)

From the above graph, one finds the average number of earthquakes per year is 141.1 times. Year 1999 has extraordinary high number of records due to the horrible 921 earthquakes, which registered with a magnitude of 7.3 in the Richter scale. The 921 Nantou earthquakes took away 2,415 lives as well as injured 11,305 people (wiki/921_earthquake). Note that from 1995 to 1998, the yearly number of earthquakes is two standard errors below mean. The energy accumulated during these (and previous) periods seemed to be finally released in year 1999.

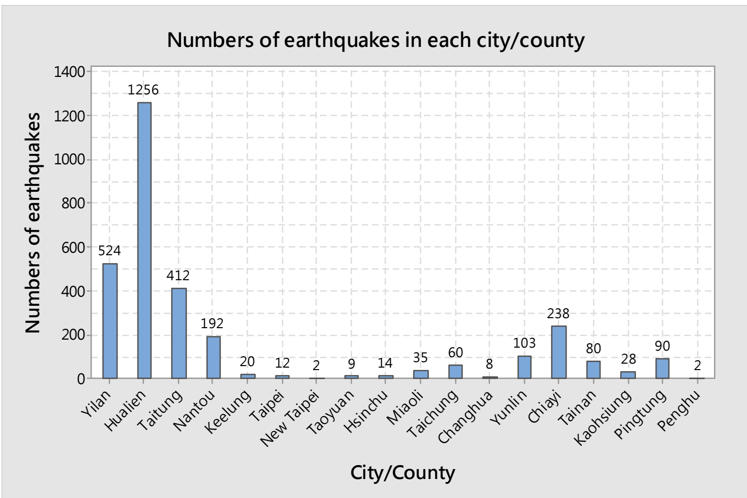

Figure 2: Total Number of Earthquakes from January 1995 to October 2016 for Each City/County in Taiwan

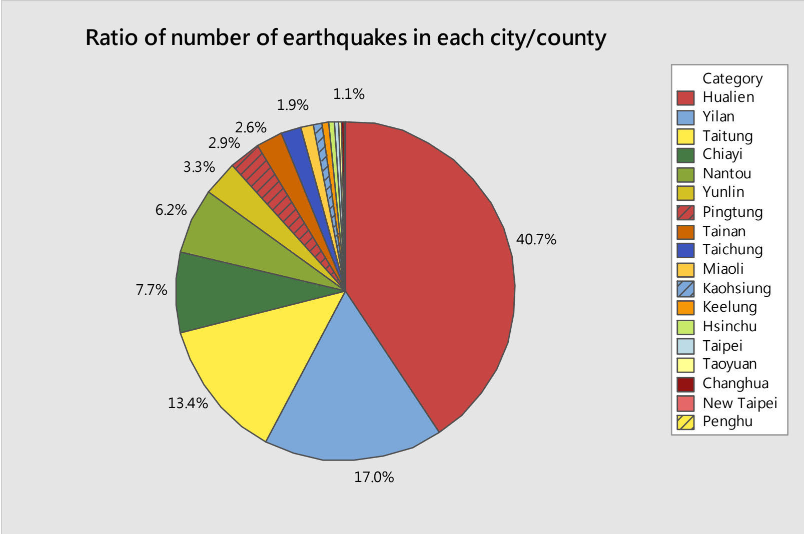

Figure 3: Percentage (%) of Frequency of Earthquakes of Each City/County to Taiwan's Total Number of Earthquakes from January 1995 to October 2016

From the above figures, one finds Hualien is the most active place for earthquakes in Taiwan. There are 1,256 out of a total of 3,085 earthquakes in Hualien, and the ratio is 40.7%. Yilan takes the second place, with 524 times (17.0%), and Taitung is the third, with 412 times (13.4%). In other words, about 71.1% of earthquakes occur in the eastern coast of Taiwan.

Mean Times per Month

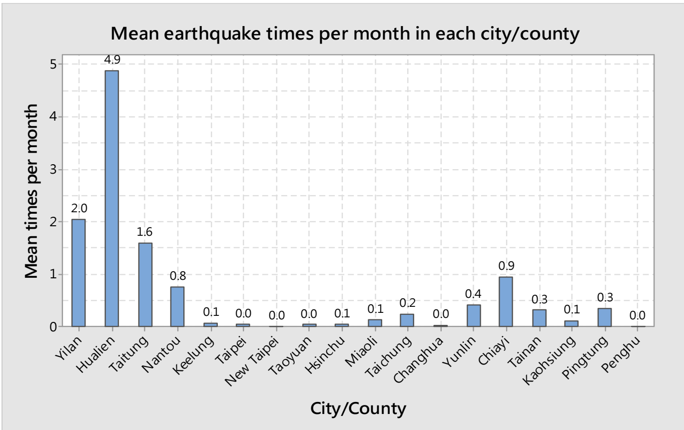

Figure 4: Mean Times of Earthquakes Per Month for Each City/ County in Taiwan from January1995 to October 2016

No doubt, Hualien is the champion of the mean times per month. In each month there are 4.9 times of labeled earthquakes there. Yilan and Taitung have 2.0 and 1.6 times respectively.

Mean Times per Year

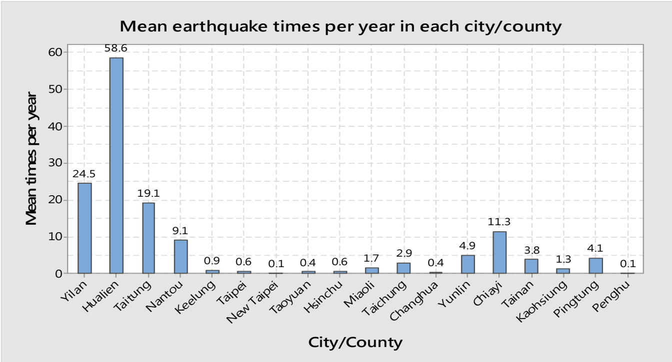

Figure 5: Mean Times of Earthquakes per Year for Each City/ County in Taiwan from January 1995 to October 2016

Hualien has the most frequent earthquake per with the number 58.6, then followed by Yilan (24.5), and Taitung (19.1).

Mean Depth (km)

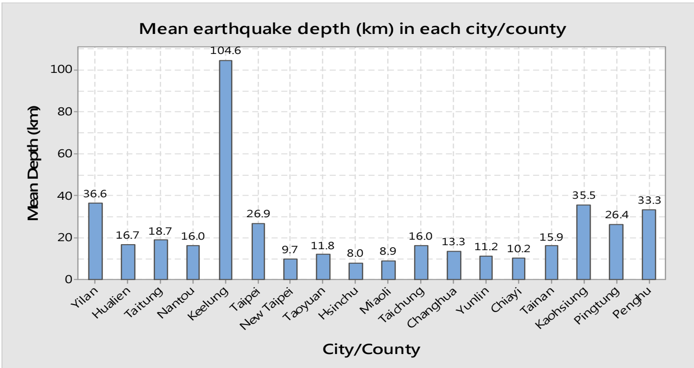

Figure 6: Mean Depth (km) of Earthquakes for Each City/ County from January 1995 to October 2016

Almost all the mean depth of hypocenters of earthquakes in Taiwan are shallow (<70 km), except Keelung (104.6 km), which is classified as intermediate-depth. Maybe it is because earthquakes in Keelung occur on the submerged tectonic plate.

Mean Magnitude (Richter scale, M_L)

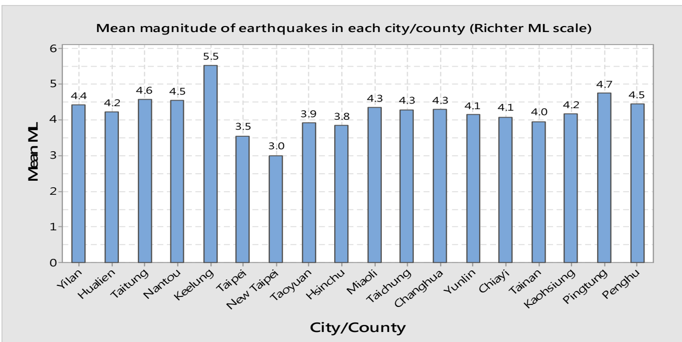

Figure 7: Mean Magnitude of Earthquakes of Each City/ County from January 1995 to October 2016

Surprisingly, the highest mean magnitude (Richter, M_L) for Taiwan is in Keelung (5.5). The mean value of magnitude of all earthquakes from January 1995 to October 2016 is 4.2 (M_L). Catastrophic earthquake has rarely occurred in Keelung, although the mean magnitude there is higher than any other places. It is probably hypocenters of earthquakes are deep in that area so the waves attenuated to the surface are less harmful.

Maximum Magnitude of Earthquakes for Each City/County in Taiwan

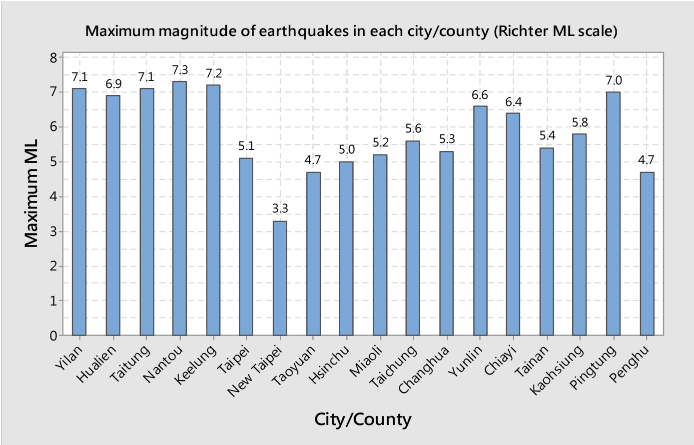

Figure 8: Maximum Magnitude (M_L) of Each City/County in Taiwan

The maximum magnitude of earthquakes in Taiwan for the past 21 years and 10 months is 7.3 (Richter magnitude scale M_L) in Nantou on September 21, 1999. Totally 2,415 people died and 11,305 were injured in that earthquake (wiki/921_earthquake). Although the magnitude of some areas are at 7.0 or above, the epicenters of them are out of Taiwan, hence much less damage was done to the Formosa Island.

Mean Time (D Time in Days) between Two Earthquakes in Each City/County

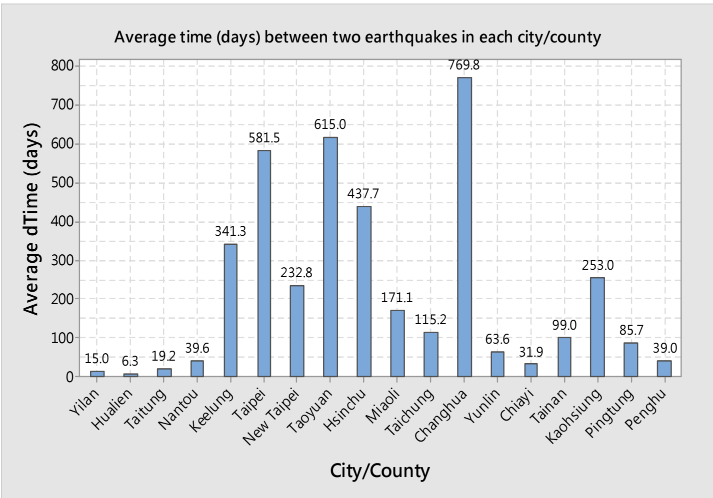

Figure 9: Mean Interval of Time (Days) between Two Earthquakes for Each City/County from January 1995 to October 2016

Mean interval of time between two earthquakes for each city/county is defined as d Time (days). In Hualien, people might experience a tremor of ground every 6.3 days while for Changhua the interval of two earthquakes takes 769.8 days. Two counties, Kinmen and Matsu are excluded from this analysis because no earthquake record has been found.

Mean Ratio of Energy (Ergs)

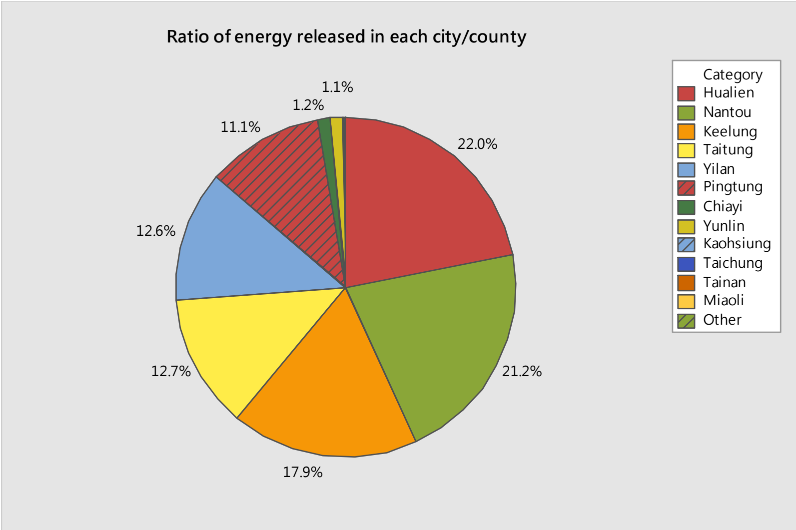

Figure 10: The Ratio (%) of Energy Released in each City/County to Total Energy Released by All Earthquakes in Taiwan from January 1995 to October 2016

The energy calculation for each earthquake is based on the equation given by Gutenberg and Richter (Kramer, 1996). The energy released from all labeled earthquakes is calculated by equation $\log_{10}E=11.8+1.5M_S$ (ergs). The energy release of total labeled earthquakes of each area to that of total labeled earthquakes in Taiwan from January 1995 to October 2016 is expressed in ratio. As expected, Hualiengrabs number one (22.0%), followed by Nantou (21.2%) and Keelung (17.9%).Note that because the energy releases of those unlabeled earthquakes are not counted, the above results are just for reference only.

STATIONARY AND AUTOREGRESSIVE CONDITIONAL HETEROSKEDASTIC (ARCH) CHARTERS OF MONTHLY NUMBER OF EARTHQUAKES IN HUALIEN AND YILAN

A stationary variable is one that is not explosive nor tending, and nor wandering aimlessly without returning to its mean (Hill et al.). If a time serious is not stationary, a danger of unrelated data may have a significant regression result. Such regressions are said to be spurious (Hill et al., Hanke and Wichern). In this study, the unit-root test Augmented Dickey-Fuller (ADF) method is used to check the stationarity of the time series of the earthquakes per month from January 1995 to October 2016.

Non-stationary time series variables should not be used in regression models for the problem of spuriousness. If variables y_i and x_i are non-stationary with integrated I(1), and their linear combination will be I(1) as well. However, if the linear combination of variable y_i and x_i becomes stationary I(0) process, then these two variables are said to be co-integrated. A natural way to test whether y_i and x_i are co-integrated or not is checking the stationarity of the residuals of the least squares by using a Dickey-Fuller test (Hill et al.). If the residuals of regression between these two non-stationary variables are stationary, then y_i and x_i are said to be co-integrated. On the other hand, if the residuals of regression are non-stationary, then y_i and x_i are not co-integrated, and any apparent regression relationship between them is said to be spurious (Hill et al.). Such spurious effect should be checked and avoided.

Autoregressive conditional heteroskedastic (ARCH) model was proposed by Nobel Prize winner Robert Engle to deal with the volatility of inflation (Engle, Hill et al.). In this study, ARCH is used to check the existence of the

heteroskedasticity of the time series of number of earthquakes per month in both Hualien and Yilan Counties. When the variances for all the observations are not the same, the heteroskedasticity exists. On the other hand, if all the variances observed are same, the time series are homoskedastic.

Characters of Monthly Number of Earthquakes in Hualien and Yilan

Two important characters, stationarity and co-integration, of the time series for monthly number of earthquakes in Hualien and Yilan will be tested in this section. The stationarity and co-integration tests are used for avoiding the spuriousness (Hanke and Wichern, Hill et al.).

Before formally checking stationarity, the plot of the monthly number of earthquakes in Hualien and Yilan from January 1995 to October 2016 as in Figures 11 and 12 are visually inspected. The I-Chart used here is purposely to weed out the months with extremely high earthquake numbers with three standard errors from the mean. Figure 11reveals that there are 14 times in Hualien in the past 262 months. The earthquakes number surpasses three standard errors above mean value, which is 4.79. As for Yilan, there are 8 times with extraordinary high monthly earthquakes as shown in Figure 12. The mean value of Yilan is 2.0 times of earthquakes per month.

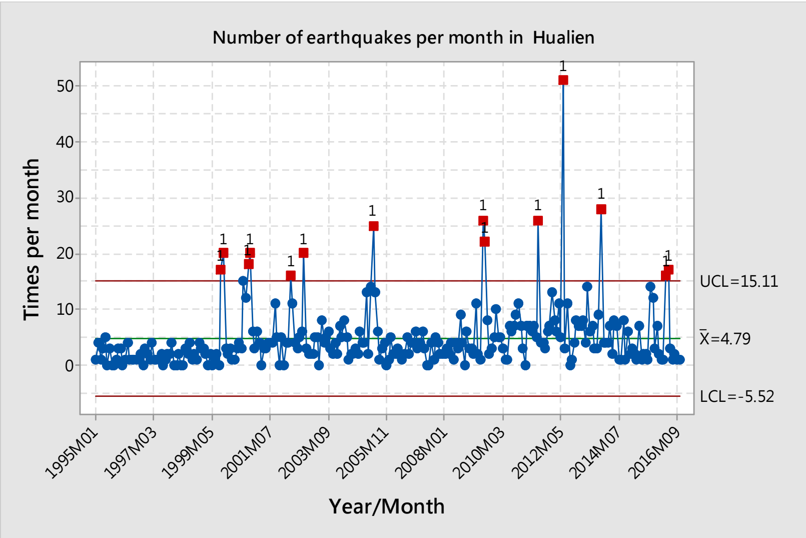

Figure 11: Number of Earthquakes per Month in Hualien from January 1995 to October 2016

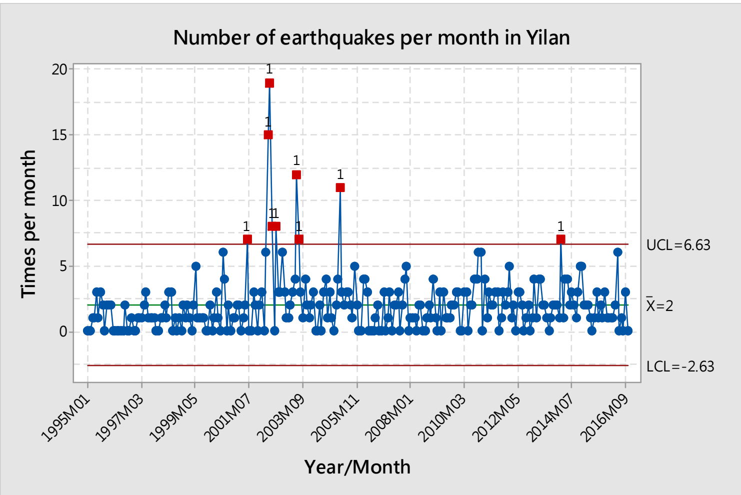

Figure 12: Number of Earthquakes per Month in Yilan from January 1995 to October2016

Stationarity

A stationary variable is one that is not explosive, nor trending, and nor wandering aimlessly without returning to its mean (Hill et al.). One can check stationarity of a time series by visual inspection of Figures 11 and 12, or by more formal tests, such as unit-root tests. Dickey-Fuller, one of the unit-root tests, is used to check the stationarity of a time series in this paper. The Dickey-Fuller test has a number of variety forms, and generally referred as the Augmented Dickey-Fuller (ADF) test (Hill et al., Hyndman and Athanasopoulos).

The Dickey-Fuller Critical Values

To test the hypothesis in all the cases, one can simply estimate the test equation by least squares and examine the *t-statistic* for checking the hypothesis condition. Unfortunately, this *t*-statistic no longer has the *t*-distribution, rather, *tau* (τ) statistic has to be used (Hill et al.). The critical values of tau (τ) statistic can also be referred to Hill et al.

Augmented Dickey-Fuller (ADF) Test

The critical values of the Augmented Dickey-Fuller (ADF) test of the time series of the monthly number of earthquakes in Hualien are shown in Table 2.

Table 2: The Critical Values and Dickey-Fuller Unit-Root Test Results for Hualien

$\tau(t)$ Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
-12.41	-3.46	-2.88	-2.57
MacKinnon approximate *p*-value for $\tau(t)$ = 0.0000			

From the above table, one finds the $\tau(t)$ test statistic -12.41< -2.88 (5% critical value), the hypothesis test $H_0 : \gamma = 0$ (non-stationary) is rejected, and $H_1 : \gamma < 0$ (stationary) is not rejected. In other words, the time series of the earthquakes per month for Hualien is a stationary one.

Similarly, the ADF test for Yilan is shown in Table 3.

Table 3: The Critical Values and Dickey-Fuller Unit-Root Test Results for Yilan

$\tau(t)$ Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
-10.52	-3.46	-2.88	-2.57
MacKinnon approximate *p*-value for $\tau(t)$ = 0.0000			

From the above table, one can also find the hypothesis test $H_0 : \gamma = 0$ (non-stationary) is rejected, and $H_1 : \gamma < 0$ (stationary) is not rejected. Hence, that the time series of earthquakes per month in Yilan is stationary can be confirmed.

Both the time series of the monthly number of earthquakes in Hualien and Yilan are stationary, then the worrisome of spuriousness can be reduced but not completely eliminated. As long as the residuals of the regression are stationary, then the co-integration can be confirmed, and the spuriousness can be eliminated. The regression result of Hualien and Yilan can be expressed as follows:

Yilan = 0.2149 Hualien (1)

The regression equation shown above means that a unit increases of earthquake in Hualien may result in an increase of 0.2149unit earthquake in Yilan.

Co-integration Test

The Augmented Dickey-Fuller (ADF) test still be used to check the co-integration test of the residuals of the regression between Hualien and Yilan, but with different critical values (Hill et al.). The results are shown in Table 4.

Table 4: Critical Values of the Co-integration Test

$\tau(t)$ Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
-11.81	-3.39	-2.76	-2.45
MacKinnon approximate *p*-value for $\tau(t)$ = 0.0000			

From the above table, one finds the $\tau(t)$ test statistic -11.81< -2.76 (5% critical value), the hypothesis test H_0 : the series are not co-integrated (residuals are non-stationary) is rejected, and H_1 : the series are co-integrated (residuals are stationary) is not rejected. In other words, the series of Hualien and Yilan are co-integrated. With both stationary and co-integrated check, one can confirm that the regression equation (Equation 1) is not spurious.

AUTOREGRESSIVE CONDITIONAL HETEROSKEDASTIC (ARCH) OF THE TIME SERIES OF HUALIEN AND YILAN

Heteroskedasticity exists when the variances for all observations are different. Conversely, when the variances are identical, the homoskedasticity exists. A variable regresses on its own lag or lags is "autoregressive." Nobel Prize winner Robert Engle's original work (Engle) on autoregressive conditional heteroskedastic (ARCH) model was concerned with the volatility of inflation (Hill et al.). However, the author takes that model and works on the time series of the monthly number of earthquakes in Hualien and Yilan. In case that the heteroskedasticity exists, the range of confidence interval obtained from the standard error of samples should also be modified. The ARCH model has become a popular one because it is useful for modeling volatility and especially changes in volatility over time (Hill et al.). The earthquake data are volatile, and ARCH may be suitable to trace the variances of such kinds of time series.

ARCH Test of Hualien

A Lagrange Multiplier (LM) test can be used to test for the presence of ARCH effects. To perform this test, one has to first test the mean equation, save and square the estimated residuals, and perform the statistic test (Hill et al., Salvatore and Reagle). The ARCH test of Hualien can be expressed in Equation 2. The *t-statistic* of the first-order coefficient ($\hat{\alpha}_1$=0.171, *t*=2.58) suggests a significant ARCH (1) coefficient. One of the requirements for the ARCH model is that $\hat{\alpha}_0$> 0 and $\hat{\alpha}_1$> 0 to make sure of the positive variance. From Equation 2, such requirements are satisfied. Hence, the null hypothesisH_0*: no ARCH* is rejected and the alternative hypothesis H_1: *ARCH (p) disturbance* is accepted.

$$\begin{aligned}\hat{h}_t &= \hat{\alpha}_0 + \hat{\alpha}_1\hat{e}_{t-1}^2 = 28.014 + 0.1710\hat{e}_{t-1}^2 \\ t-value & \qquad\quad (29.63) \quad (2.58)\end{aligned} \tag{2}$$

Where

$\hat{h}_t =$ estimated variance of residual at time *t*

$\hat{\alpha}_0, \hat{\alpha}_1 =$ coefficients to be determined

$\hat{e}_{t-1} =$ error term at time *t-1*

The results of the ARCH (1) model are shown in Figure 13. From the figure, it is obvious for one to observe the volatility of variances in the time series of the monthly number of earthquakes in Hualien.

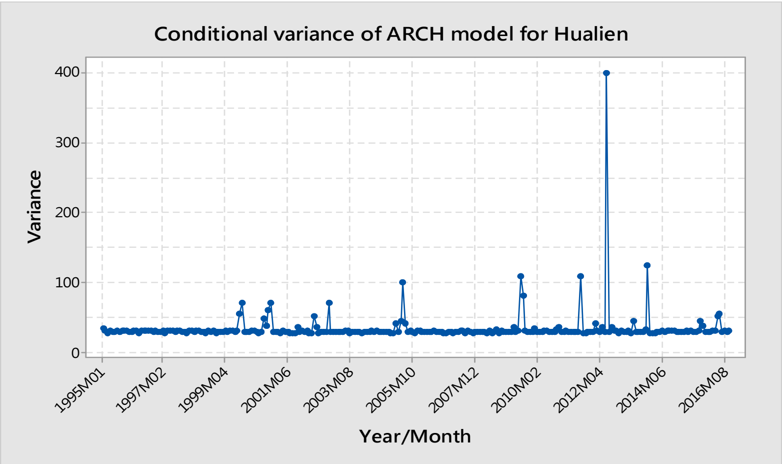

Figure 13: Variances of Autoregressive Conditional Heteroskedasticity (ARCH) Model for Hualien

ARCH Test of Yilan

The ARCH test for Yilan is the same as the previous subsection of Hualien, only the analysis results are shown in this subsection. The estimated variance $\hat{h}_t$ at time *t* is shown in Equation 3, and from the t-statistic, the significant ARCH (1) coefficient is suggested. Hence, the null hypothesis*H_0: no ARCH* is rejected and the alternative hypothesis *H_1: ARCH (p) disturbance* is accepted.

$$\begin{aligned} &\hat{h}_t = \hat{\alpha}_0 + \hat{\alpha}_1 \hat{e}_{t-1}^2 = 1.942 + 0.718\hat{e}_{t-1}^2 \\ &t - value \qquad\qquad (8.86) \quad (7.97) \end{aligned} \qquad (3)$$

The results of the ARCH (1) model for Yilan are shown in Figure 14. From the figure, it is obvious for one to observe the volatility of variances in the time series of the monthly number of earthquakes in Yilan.

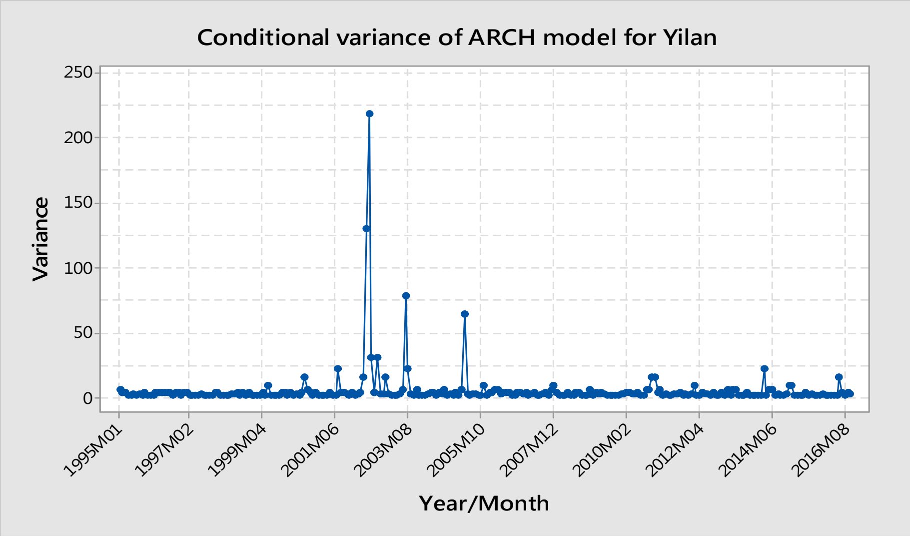

Figure 14: Variance of Autoregressive Conditional Heteroskedasticity (ARCH) Model for Yilan

CONCLUSIONS

After analyzing earthquake data in Taiwan from January 1995 to October 2016and scrutinizing the characters of monthly number of earthquakes in Hualien and Yilan the following conclusions can be obtained:

- Hualien is the most active place for earthquakes in Taiwan. There are 1,256earthquakes in Hualien out of totally 3,085earthquakes in Taiwan, and the frequent ratio is 40.7%. Yilan takes the second place, occurring 524 times with the ratio of 17.0%. Taitung with 412 times is the third, with the ratio of 13.4%.
- In each month, 4.9 times of labeled earthquakes happened in Hualien, 2.0 times in Yilan, and 1.6 times in Taitung respectively.
- The highest frequency of earthquakes per year is in Hualien with a number of 58.6, and followed by Yilan (24.5), and Taitung (19.1).
- Almost all the mean depth of hypocenters of earthquakes in Taiwan is shallow (<70 km), except Keelung (104.61 km), which is classified as intermediate-depth. Maybe it is because earthquakes in Keelung are in the submerged tectonic plate.
- The highest mean magnitude (Richter, M_L) for Taiwan is in Keelung (5.5, M_L). The mean value of magnitude of all earthquakes from January 1995 to October 2016 is 4.2 (M_L).
- The maximum magnitude of earthquakes in Taiwan for the past 21 years and 10 months is 7.3 (Richter magnitude scale, M_L) in Nantou on September 21, 1999.
- In Hualien, people there might experience a tremor of ground every 6.3 days, and in Changhua theinterval between two earthquakes takes 769.8 days, which is the longest in Taiwan.
- The unit-root test Augmented Dickey-Fuller (ADF) is used to test the stationarity of the time series of Hualien's monthly number of earthquakes. The hypothesis test $H_0 : \gamma = 0$ (non-stationary) is rejected, and $H_1 : \gamma < 0$ (stationary) is not rejected. In other words, the time series of the monthly number of earthquakes per month in

Hualien is a stationary one. By means of the same method, the time series of the monthly number of earthquakes per month in Yilan is also a stationary one.

- The co-integrating relationship between the time series of the monthly number of earthquakes from January 1995 to October 2016for both counties exists. Hence, the following regression relationship is not spurious. *Yilan = 0.2149 Hualien*
- The regression equation shown above means that a unit increases of earthquake in Hualien may result in an increase of 0.2149unit earthquake in Yilan.
- From the result of the ARCH (1) model, it is obvious for one to observe the volatility of variances in the time series of the monthly number of earthquakes in Hualien. In other words, variances of the Hualien time series show the effect of heteroskedasticity.
- From the result of the ARCH (1) model, it is obviously for one to observe the volatility of variances in the time series of the monthly number of earthquakes in Yilan. In other words, variances of the Yilan time series also show the effect of heteroskedasticity.

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